Artemis Project

Analysis of recovery buoy for Artemis

Author: Arthur Sale
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Executive Summary

It is planned to fit a recovery buoy to Artemis*, rather than arranging for* Artemis *to surface for recovery. This buoy is based on the Fiobuoy concept (Fiomarine 2003). This will save the carriage of compressed air tanks, main ballast tanks, and associated valve gear. It will also provide for recovery even if Artemis is severely damaged. It is necessary to model the design to determine desirable design features. The scheme is applicable to 100m depths, but probably not much more.*

Analysis

Model

The recovery buoy is modelled as a reel of line, where the reel is positively buoyant, and the line leads vertically down and is fastened to a seabed object (the landed *Artemis*).

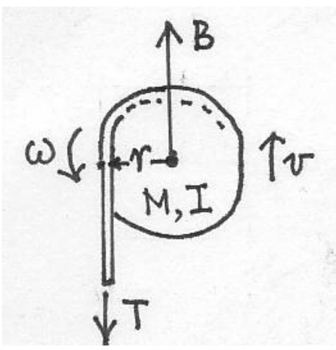
Before and during deployment

The recovery buoy is housed within *Artemis* with the line fully wound up and attached by a shackle at the bitter end to *Artemis*. One possible configuration is to have it contained in a horizontal cylindrical bay. Deployment will be achieved by opening the bay doors (like the space shuttle) or a lid. The already horizontal reel will unwind out of the housing.

It contributes a static lift dependent on the displacement and the weight of the line and the reel, and this will be accommodated in the vehicle's mass and displacement budget. Positive buoyancy must be maintained even at maximum operational depth.

Mid-water

The external forces acting on the reel at a particular instant are diagrammed below.



The equations of motion are:

$$(B - T) - K_t v^2 - M\frac{dv}{dt} = 0 \qquad \text{vertical motion}$$

$$Tr - K_r \omega^2 - I\frac{d\omega}{dt} = 0 \qquad \text{rotation about horizontal axis}$$

$$\omega = \frac{v}{r} \qquad \text{coupling, provided } T \geq 0$$

Where (SI units shown in parentheses):

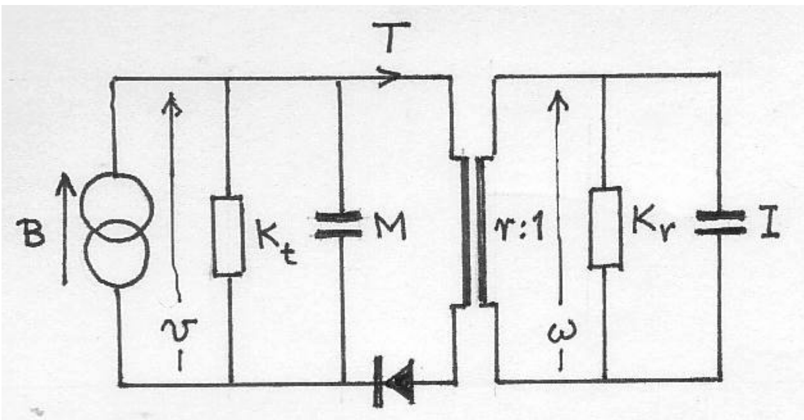
- r = Radius at which line is unrolling from reel (m)
- B = Buoyancy Force of reel and line on reel (N)
- T = Tension in line; $T \geq 0$, since it cannot sustain compression (N)
- M = Mass of reel and line on reel (kg = N/(m/s^2))
- I = Moment of Inertia of reel and line (kg-m = N-m/(1/s^2))
- K_t = Translational Drag Coefficient of reel and line on reel (N/(m/s)^2)
- K_r = Rotational Drag Coefficient of reel and line on reel (N-m/(1/s)^2)

Note that all of these parameters are functions of the amount of line left on the reel (or equivalently the amount unrolled), which is itself a function of the time t since release. However, K_t and K_r are probably only weakly dependent on this factor, and if the line is neutrally buoyant B depends only on the reel and is constant.

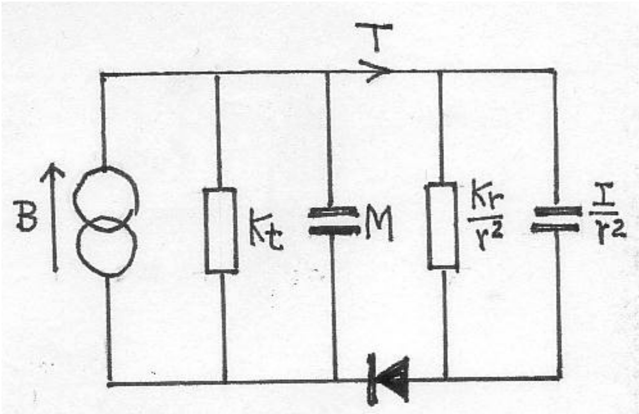
Drag forces are assumed to depend on velocity squared, which is approximately true for frictional and turbulent drag. This and the other varying parameters invalidate linear analysis of the travel of the reel upwards.

However, admitting square-law conductances ($V \propto I^2$), a simple electrical equivalent circuit can be drawn, using the following equivalences. This provides a quick appreciation of the main features of the dynamic behaviour.

Mechanical	Electrical
Force, Torque	Current
Velocity, Angular velocity	Voltage
Rigid object, static reference	Node
Drag (square-law)	Conductance (square-law)
Mass, Moment of Inertia	Capacitance
Compliance, springiness	Inductance
Coupling	Ideal transformer



This circuit can be reduced to a simple RC circuit by pushing the rotational network through the ideal transformer.



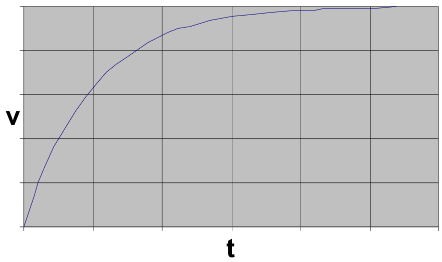
From this we can deduce that (a) the tension T will never reach 0 so the coupling equation will hold, and (b) the reel will accelerate monotonically upwards to an asymptotic terminal velocity relevant to its current state of unrolling. If the conductances were linear, the speed would follow

$$v = v_{final}(1 - e^{-\frac{t}{\tau}})$$

in the short-term, where

τ = time constant

v_{final} = the terminal velocity



In the actual case where drag is proportional to speed squared, the approach to steady state will still be monotonic, but the initial rise will be faster than in the linear case. Consider the steady state when $\frac{dv}{dt} = 0$ and $\frac{d\omega}{dt} = 0$, so defining

$$\alpha = \frac{K_r}{K_t} \times \frac{1}{r^3}$$ a dimensionless value in [0..∞]

then the terminal velocities can be shown to be

$$v_{final} = \sqrt{\frac{1}{1+\alpha} \times \frac{B}{K_t}}$$

$$\omega_{final} = \frac{v_{final}}{r}$$

and the tension in the line T is

$$T = \frac{\alpha}{1+\alpha} B$$ note $0 \le T \le B$

Tangling

Loss of tension in the line leads to risk of the reel over-running itself and the line becoming tangled, leading to cessation of unrolling and a system failure. The above analysis shows that there is never any risk that $T = 0$ in quiet waters.

However, it is possible that a downward eddy will push the reel down and lead to loss of tension in the line. The highest probability occurs near the surface due to wave action. Four factors then come into play: (a) the eddy must have a velocity at least equal to v, (b) the line in the vicinity of the reel should be equally affected by the eddy, (c) if the tension in the line drops to zero a low translational drag coefficient K_t should lead to a rapid upward acceleration and line tautening, and (d) a high rotational drag coefficient K_r should reduce the spin of the reel rapidly.

The two drag coefficients are thus important design parameters. A reasonable compromise would seem to be to choose $\alpha_{min} = 1$ which gives $T_{min} = 0.5\ B$. The constraint to achieve this is:

$$\frac{K_r}{r_{max}^3} \geq K_t$$

and this occurs when the line is fully wound and the reel has just left its housing. Performing some further modeling, assume that the reel has an outside wound radius of 100mm, axial length of 200mm, and contains 100m of 5mm Ø line wound 40 turns per layer. Then the inner radius of the reel is 77mm, and at the surface $\alpha \approx 2$ and $T = {}^2/_3\ B$.

Recovery

Carrying a buoy in Artemis will allow for easy recovery from a boat. There will be no need to put a diver in the water to attach a cable as with recovery of a floating vehicle; instead boathook recovery of the buoy will be possible and consequent attachment to a recovery crane and winch.

Unlike the original Fiobuoy, the line and reel are carried around as dead load on the vehicle. Thus the size of the line is an important design parameter, as it determines the reel dimensions and the dry weight contribution. Gross oversizing is not an option, though loss of the vehicle is equally unpalatable.

Let M_{wet} be the mass of the vehicle and its contained free-flooding volumes. The load on the line when the reel is being deployed is minor ($\leq$ B). Since the vehicle was neutrally buoyant before deployment of the buoy, the steady load on recovery is only B, until the vehicle breaks surface when the load will become $g.M_{wet}$, dropping as free-flooding areas drain to $g.M_{dry}$.

A dynamic load also occurs during recovery. Assume there is a mass of M_{wet} at the end of the line, and the recovery vehicle is moving vertically in a sea lifting the surface end of the line up and down. Assume also that the motion is sinusoidal with an amplitude of A metres, and a frequency of f. Then the motion of the upper end of the line is described by:

$$z = A \sin(2\pi f t)$$

$$\frac{dz}{dt} = (2\pi\ f)\ A \cos(2\pi\ f\ t)$$

$$\frac{d^2 z}{dt^2} = -(2\pi\ f)^2\ A \sin(2\pi\ f\ t)$$

The highest forces will occur when the vehicle is about to break the surface and little line is deployed. When the vehicle is at depth, the payed-out line will act as a spring or a compliant transmission line, and the forces on the vehicle will be lower.

Assume that there is no compliance in the line, and that fluid resistance of the line and vehicle can be ignored. Then the maximum upward acceleration due to the surface motion will be $(2\pi f)^2 A$ and thus the force on the vehicle will be

$$(2\pi f)^2 A\, M_{wet}$$

This needs to be multiplied by two to account for shock loads due to the line becoming slack on a down heave and suddenly becoming taut on an upward one. Translating this into dominant significant wave height H (= $2A$) and period P (= $1/f$):

$$F_{\max} = 4\pi^2 \frac{H}{P^2} M_{wet}$$

Reduced loads can be achieved by a length of suitably sized shock-cord at the attachment of the vehicle and the line, or by a compliant crane design (either like a flexible fishing-rod, a shock absorber in the line path, or a torque-adjusted slipping winch). If M_{wet} = 50kg, H = 5m, and P = 5s, then F_{max} = 400N, or 41kgf. This is comparable to the weight of the vehicle.

Design

Buoyancy

The reel should be made of buoyant solid material with no internal air spaces, unless it carries a surface radio beacon. See later regarding the buoyancy of the line..

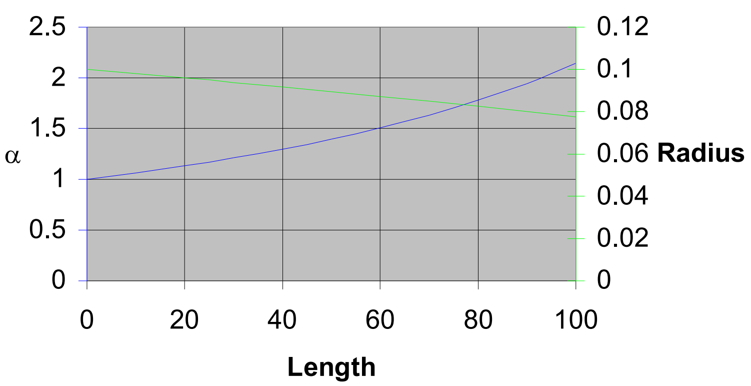
Reel

If the outer radius of action of the fully wound up reel r_o is determined by the vehicle dimensions, ℓ is the unrolled length of line, d is the line diameter, and N is the number of turns per layer, then the operational radius for any degree of deployment can be determined from:

$$\ell = \frac{\pi N}{d}(r_o^2 - r^2)$$ (treats layer effects as continuous)

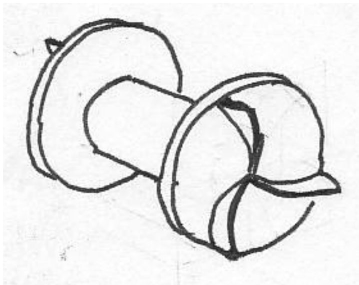
$$r = \sqrt{r_o^2 - \frac{\ell d}{\pi N}}$$

The radius of the inner drum is therefore $r_{drum} = r_{\ell \max} - \frac{d}{2}$.



Drag design

It seems likely that the rotational drag of a simple reel would be low with respect to the translational drag. The problem would appear to be one of increasing the rotational drag coefficient without increasing the translational drag coefficient. Given the buoy is housed in Artemis, a solution that does not increase the diameter seems desirable. One possible solution is sketched; drag fins/ridges similar to a centrifugal pump impellor would be moulded on both reel sides.



Stability

The above analysis assumed that the reel assumes a position with its axis horizontal, and travels upwards in this position. The hydrodynamic stability of this configuration is not known at this stage, but it would appear to be wise to keep the axial length less than or equal to the diameter of the reel. Some experiments should be conducted or further research undertaken.

The spin may provide some gyroscopic stabilization for this attitude. If this is considered desirable, the effect can be enhanced by increasing the Moment of Inertia I through the off-axis mass distribution.

The above analysis has ignored a horizontal hydrodynamic 'lift' (Magnus effect) that would be generated by the rotating and rising reel. It seems likely that this would be small and not affect the behaviour much. Keeping the translational velocity low helps in this regard, since

Lift force = $\rho \, 2\pi \, r_o \, v^2$

Line

A line breaking strain ≥ 200kgf should be sufficiently strong. For example typical 5mm rope has breaking strain >320kgf and dry weight ~0.95kg/100m. Braided rope may be preferable to laid rope to minimize twist and kinking.

Slightly positive buoyancy may be more desirable than neutral buoyancy to avoid snagging of Artemis on the seabed by surplus line after the buoy has reached the surface. This will change the analysis slightly by reducing B as the buoy rises.

References

Fiomarine (2003). Fiobuoy web site. **2003**. http://www.fiomarine.com/